
Cathode Research and the Threshold Cathode Test Facility

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Final Report

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TABLE OF CONTENTS

INTRODUCTION	1
MOTIVATION	1
EXPERIMENTAL ASSEMBLY	2
SPACE CHARGE-LIMITED FLOW SIMULATIONS	5
SUMMARY	6
REFERENCES	7

LIST OF FIGURES

FIGURE 1. TCTF VACUUM SYSTEM (LEFT) AND PULSED POWER TANK (RIGHT) AS ASSEMBLED AT THE AIR FORCE RESEARCH LABORATORY, DIRECTED ENERGY DIRECTORATE AT KIRTLAND AFB, NM,	2
FIGURE 2. TYPICAL RESIDUAL GAS ANALYSIS (RGA) SPECTRUM AT A CHAMBER PRESSURE OF 8×10^{-8} T. BACKGROUND GAS CONSISTS MAINLY OF NITROGEN (28 AND 14 AMU), HYDROGEN (2), OXYGEN (32, 16), WATER (18, 17), CARBON DIOXIDE (44), AND ARGON (40).	3
FIGURE 3. VOLTAGE (LEFT) AND CURRENT (RIGHT) WAVEFORMS FOR VARIOUS APPLIED VOLTAGES. CATHODE IS MADE OF CESIUM IODIDE-COATED CARBON FIBER TUFTS.	5

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INTRODUCTION

The Department of Defense's investment in directed energy weapons research has led to exceptional advances in both high tech lasers and high power microwave (HPM) devices. For HPM systems, next-generation devices will require higher output powers from smaller and lighter packages. Since the output power available from an HPM device is directly proportional to the input power of the driving electron beam, one must increase either the beam voltage or current to increase the microwave power. Increasing the beam voltage deleteriously increases the size and weight of the total HPM system in several ways, *e.g.*, increased power supply volume and weight, a required increase in interface and voltage standoff dimensions, and the increased interaction length necessary for a more relativistic electron beam. Thus, in an effort to increase the total current in the electron beam as opposed to increasing the beam voltage, much research into the cathode emission process has been performed over the past twenty years.¹⁻³ There are a number of specific areas for improvements in cathode technology that will do much to advance the state-of-the-art in HPM generation: emission current density, beam quality, efficiency, fabrication cost, operability in a hostile environment, lifetime, plasma generation, and voltage threshold for emission. The purpose of the Threshold Cathode Test Facility (TCTF) research program is to investigate the electron emission properties of various cathode materials under the HPM-relevant conditions of high electric field stress in a high vacuum environment. Over the course of the present R&D effort, TCTF was designed, built, and tested at the Air Force Research Laboratory (AFRL), Directed Energy Directorate at Kirtland AFB, NM. In addition, simulations were performed that shed new light on the performance of space charge-limited cathodes in realistic geometries.

MOTIVATION

Explosive emission cathodes are the most popular choice for providing the multi-kiloampere beam currents required in today's HPM sources.¹⁻³ Nevertheless, the complete physics of the explosive emission process is far from fully characterized. While it has been experimentally observed that anode/cathode materials, anode/cathode temperatures, background vacuums, and cathode coatings (such as cesium iodide) all have dramatic influence on explosive emission operation,⁴⁻⁸ it is still not possible to quantitatively predict from first principles each effect so that diode design and simulation can progress independent of experimental verification. In pursuit of a robust, reproducible, vacuum-compatible, long-lived cathode for use in HPM devices, the Threshold Cathode Test Facility is designed to investigate many basic physics issues underlying a variety of explosive emission cathodes in several different operating environments. The ultimate goal is to attain not only the desired cathode properties but also the ability to predict and simulate how changes in the diode environment will affect these properties.

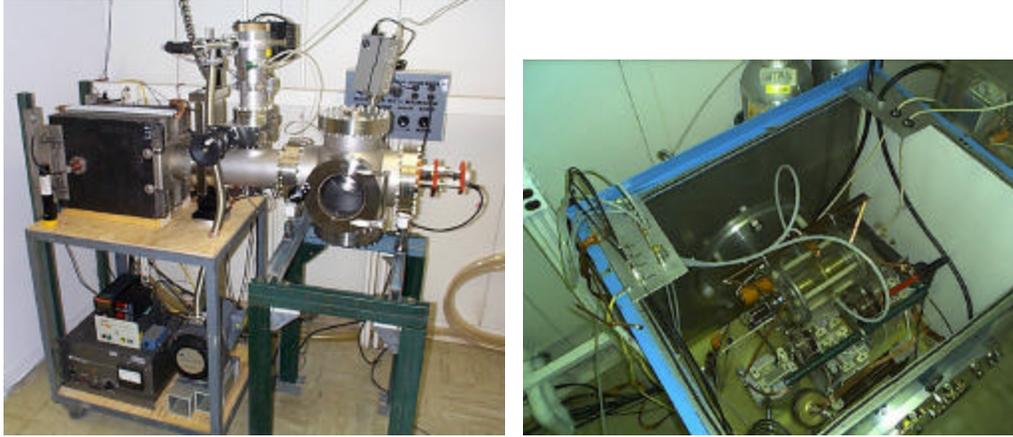


Figure 2. TCTF vacuum system (left) and pulsed power tank (right) as assembled at the Air Force Research Laboratory, Directed Energy Directorate at Kirtland AFB, NM.

EXPERIMENTAL ASSEMBLY

As constructed during performance of this R&D effort, the Threshold Cathode Test Facility consists of an ultra-high vacuum system (stainless steel vacuum vessel, pumps, valves, gauges, etc.), a pulsed power system for applying a high voltage, short duration impulse to the cathode (mounted inside the vacuum system), and a variety of diagnostics and support equipment. The exterior of the vacuum system and the interior of the pulsed power tank are shown in Fig. 1.

The TCTF vacuum chamber has a stainless steel 30 cm diameter spherical body with six copper gasket-seal flanges; the total system volume is approximately 47 liters. All main peripheral seals are also copper gaskets except for an elastomer-sealed access door and elastomer seals in two gates valves used for pump/chamber isolation. The turbo pump used is backed by a completely oil-free scroll pump and is supplemented by a large ion pump; the turbo system is used during roughing and during gas flow experiments, while the ion pump is used to achieve ultimate base pressure. Vacuum pressures are measured both at the turbo pump and at the test chamber by convection gauges (atmospheric to a few mT) and by cold cathode inverted magnetron gauges (a few mT down to UHV). A UHV-compatible 600 W quartz heating lamp is mounted internally so that it can effectively bake/outgas the majority of the internal surface area. When the chamber must be let up to atmosphere, the lamp is kept on at a reduced level in order to discourage water adsorption. Using this scheme, the chamber can be pumped from atmospheric pressure into the 10^{-7} T scale in approximately twenty minutes. A base pressure in the low 10^{-7} T scale is reached within a few hours, while the high 10^{-8} T scale is accessed after heating overnight with the quartz lamp. Bake temperature must be kept below 150° C due to various electrical components mounted on the chamber. Post bake-out pressures are in the mid 10^{-9} T scale.

The vacuum system is also equipped with an extremely fine-control leak valve so that small amounts of gas (e.g. air, nitrogen, argon, etc.) may be flowed through the chamber. Such fine control will allow for the examination of cathode performance versus background pressure with the background pressure controlled to within 1×10^8 T. A residual gas analyzer (RGA) mounted near the main chamber gives quantitative information on background gas constituents and their partial pressures. With the RGA's electron multiplier functioning, partial pressures can be detected down to the 10^{12} T scale for any gas species up to two hundred atomic mass units. Thus, even minor amounts of contaminants can be detected against a large background of nitrogen, hydrogen, and/or water vapor. A typical RGA spectrum is given in Fig. 2 to illustrate the background gases present at a base pressure of 8×10^8 T. Such a tool is invaluable when determining the quantities and identities of gas species produced by explosive emission from various cathodes and will also help monitor the purity of introduced gases during pressure versus cathode performance tests.

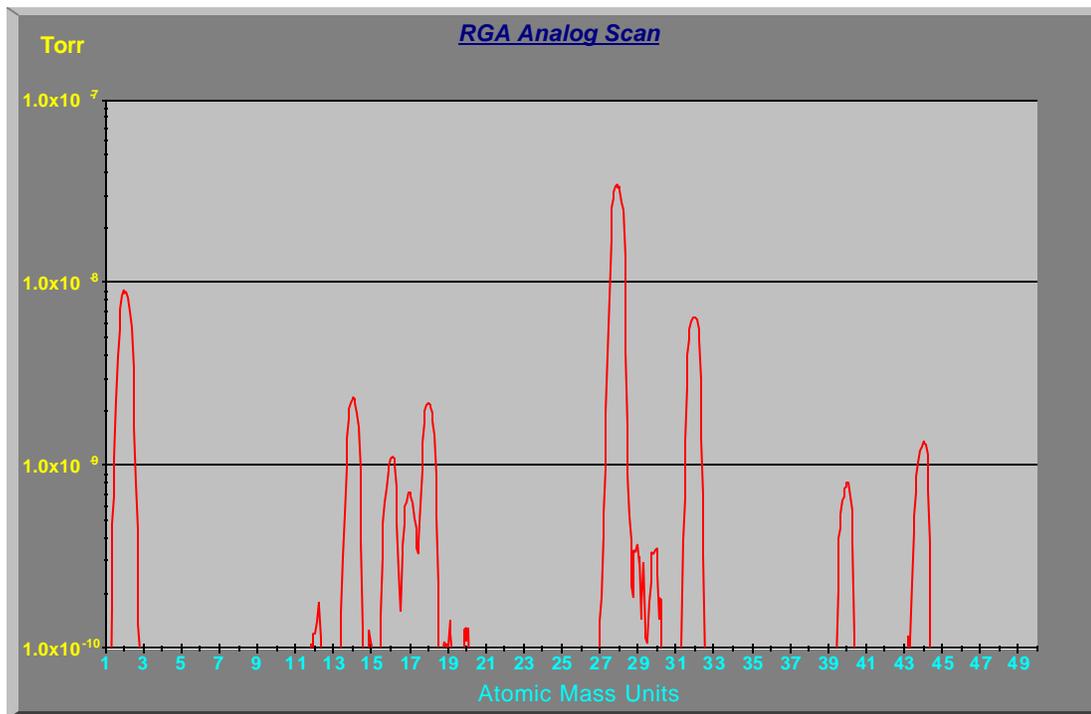


Figure 3. Typical residual gas analysis (RGA) spectrum at a chamber pressure of 8×10^8 T. Background gas consists mainly of nitrogen (28 and 14 AMU), hydrogen (2), oxygen (32, 16), water (18, 17), carbon dioxide (44), and argon (40).

The present vacuum system provides an extremely fine control over the cathode testing environment. The mid 10^6 T scale corresponds to a monolayer formation time of just a single second, so many previous cathode experiments were most likely dominated by the adsorbants on cathode surfaces rather than by the cathodes. Every order of

magnitude improvement in pressure increases the monolayer formation time by an order of magnitude as well; thus, in the 10^{-8} T scale, even with a single-shot pulsed power system, one may fire shots often enough to prevent electrode surface monolayer formation. The small total volume of the vacuum system makes electrode outgassing effects that much more significant. For additional sensitivity, the pumps may be valved-off from the chamber altogether so that all gases generated in an emission pulse are trapped within the system and may be detected by the RGA. The addition of the precision leak valve and RGA allows the user to not only modify the vacuum environment but also completely characterize it.

The pulsed power system is a 200 kV, 2.2 kJ Marx bank for energizing the vacuum diode. The modulator is designed to be generally operated in single shot mode, but is capable of ~ 0.5 Hz repetition rate bursts for up to 1 minute (limited by excessive heating of the crowbar circuit resistor). The output of the Marx is adjustable from -50 kV to up to -200 kV. Pulse duration is also adjustable from ~ 200 ns to ~ 2 μ s via a triggered crowbar circuit. The pulse is delivered to the cathode via ~ 2 m of RG-220 coaxial cable. The high voltage vacuum interface is a custom vacuum envelope consisting of a pair of 10" diameter Conflat flanges on either end of an alumina ceramic insulating cylinder (8" dia. x 7.5" tall). The exterior of the interface is enveloped in a bladder filled with SF₆ in order to prevent arcing along the outside of the ceramic. The adjustable voltage magnitude and anode-cathode gap separation allows for TCTF testing at applied electric fields between 50 - 275 kV/cm for drawn current densities between 40 - 400 A/cm². Sample voltage and current waveforms from initial tests of a CsI-coated carbon tufted-fiber cathode are shown in Fig. 3. Further details on the vacuum system, pulsed power, and design of the cathode/anode geometry can be found in Ref. 9.

Varying V at 10^{-4} Torr

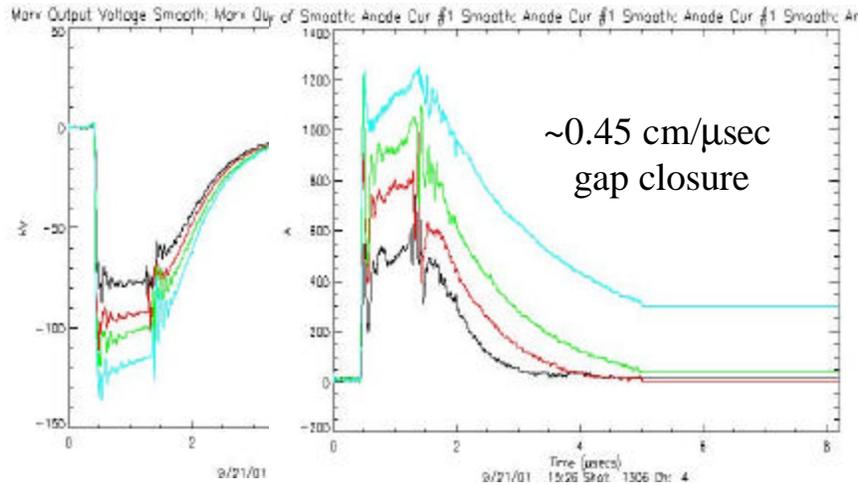


Figure 4. Voltage (left) and current (right) waveforms for various applied voltages. Cathode is made of cesium iodide-coated carbon fiber tufts.

SPACE CHARGE-LIMITED FLOW SIMULATIONS

In addition to the experimental work performed on this task, analytic and computational tools were also employed to examine space charge-limited flow in geometries applicable to explosive emission cathodes. A series of studies were performed which extended our fundamental understanding of electron emission limits beyond previously described one-dimensional systems. This description of two-dimensional emission effects improves both our prediction accuracy as well as our understanding of cathode physics. While these efforts have been focused primarily on basic R&D, spin-offs of this work have already shown themselves in confirmation of these 2-D effects from in-house experimental cathode tests as well as from actual HPM device results. Specifically, these 2-D simulations predict that identical total currents can be drawn from cathodes of the same bulk area even though they may vary significantly in micro-geometry; such an effect was confirmed through in-house experiments¹⁰⁻¹³ that used a variety of cathode materials and micro-geometries yet observed the same total current in each case. In addition, this work has shown that extremely small changes in local electric field near the cathode edge can drastically alter the current density being drawn from that edge; one such example is the “field-shaper” cathode that helped moderate high current-density flares inside AFRL’s Magnetically Insulated Line

Oscillator (MILO) HPM device¹⁴⁻¹⁵ thereby resulting in improvements of pulse duration as well as reproducibility. Both of these results are encouraging in light of the need to reduce the neutral gas production of these cathodes: 1) The amount of cathode gas production can be reduced significantly by reducing the active micro-geometry area of a cathode *without resulting in a reduction in the total supplied current*. 2) The additional gas loading that is produced from interception of high current density flares can also be mitigated by implementing very small geometry changes near the edges of cathodes in existing HPM devices. It is precisely results such as these that allow for increasing the available repetition rate of state-of-the-art HPM sources in preparation for the future needs of the Air Force. Additional details on the simulations and results can be found in Ref. 16.

SUMMARY

For the first time, an ultra-high vacuum compatible test stand for explosive emission studies has been assembled and tested. The variety of vacuum diagnostics and diode diagnostics will shed new light on the fundamental physics of explosive emission. The small total volume of the TCTF chamber (roughly equivalent to an HPM device volume) will also allow for a series of precise vacuum effects and outgassing measurements. To complement residual gas analysis, spectroscopic capabilities are present to analyze light emission from the diode region thereby providing atomic/ionic species information. Cathodes that show promising performance under the HPM-relevant electric field and current densities probed by TCTF may then be scaled up for testing on other devices under the higher total voltages and total currents required by HPM sources. Such cathodes may then be transitioned into providing the electron beam for an operational HPM device.

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